LBL-17050
SSC-MAG-4

EFFECT OF MANUFACTURING ERRORS ON FIELD QUALITY OF THE LBL SSC DIPOLES*

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January 1984

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Dept. of Energy, under Contract No. DE- AC03-76SF00098.

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Summary

A method is developed for determining the field aberrations resulting from specific kinds of manufacturing errors. This method is applied to the 40-mm i.d. dipoles under consideration at LBL, and also to similar ones with 30 and 50 mm i.d. The method is also applied to the CBA and Doubler/Saver magnets and the results compared with the measurements. The results obtained by this method are also compared with those obtained by assigning identical errors to the positions of the edges of all the coil sectors.

Introduction

Figure 1 shows a cross section of the kind of magnet under consideration.

The coil cross section is represented by a group of cylindrical sectors (which we call "blocks" out of habit) with the current density varying as $1/r$, and independent of θ, within each sector (Fig. 2). For this model the field multipole coefficients (defined later) can be determined analytically, along with their partial derivatives with respect to r_1, r_2, θ_1, and θ_2, of each sector.(1)

The effect of manufacturing errors on field quality is determined in the following way:

We identify, in terms that are meaningful to magnet designers and manufacturers, the kinds of dimensional errors that can occur in coil manufacture, and we assign numerical values to them. These manufacturing errors can be expressed as combinations of variations of r_1, r_2, θ_1, and θ_2 of the various blocks. Then, using the partial derivatives, we calculate the effects of the manufacturing errors on the field multipole coefficients. Finally we combine, in rms fashion, the effects of all of the manufacturing errors upon each field multipole coefficient

Field Representation

We represent the magnetic field in the magnet aperture in terms of multipole coefficients

$$c_n = a_n + ib_n$$

where n is the number of pole pairs associated with a particular field aberration (dipole, n = 1; quadrupole, n = 2, etc. Note that this nomenclature is different from that used by some others). The term a_n represents a "skew" component ($B_y = 0$ for $y = 0$), while b_n represents a "non-skew" component ($B_x = 0$ for $y = 0$). The magnitude of the multipole coefficient is the magnitude of the corresponding field component at an arbitrary normalizing radius ρ, which we take as 10 mm in this study. The field, then, can be represented by the equation

$$B^* = B_x - iB_y = \sum_{n=1} c_n (z/\rho)^{n-1} \text{ , where } z = x + iy$$

Application to LBL 40-mm I.D. Dipoles

Coil Dimensions

In this study, we use the dimensions given in Table 1. This represents a rough approximation to the proposed SSC dipoles under development by LBL.

Table 1

Coil Dimensions

Layer	No. of conductors	r_1 (mm)	r_2 (mm)	a_1 (deg.)	a_2 (deg.)
1	17	20.00	29.37	0	76.855
2	18	29.97	38.61	0	42.120

The current is the same in both layers.

Relation Between Manufacturing Errors and Block Dimensional Errors

These relationships are presented in Tables 2 and 3.

Table 2 shows how a particular manufacturing angular error, ε, affects the angles θ_1, and θ_2 in each quadrant. For example, if the upper pole piece is off center by an angle ε in the ccw direction (code A11), then in quadrants 1, 2, 3, and 4 respectively, θ_1 is increased by amounts $1/2\ \varepsilon$, $-1/2\ \varepsilon$, $1/2\ \varepsilon$, $-1/2\ \varepsilon$, and θ_2 is increased by amounts ε, $-\varepsilon$, 0, 0. Since this error can occur in either the top or bottom pole piece we say there are two "occurrences", and we add the effect twice in calculating the rms values of the multipole coefficients. This error could apply to either the inner or the outer layer independently, or to both layers collectively.

Table 3 shows similar data for radial position errors. Conceivably the errors could occur in each quadrant independently, in all four quadrants collectively, or in pairs of quadrants with various signs. Only the most likely combinations have been listed.

Manufacturing Errors; Numerical Values

These are presented in Tables 4 and 5 for azimuthal and radial errors, respectively.

In Table 4, the "case" designation correspond to the "code" designation of Table 2, with the addition of a 1, 2, or 3 to designate, respectively, the inner layer only, the outer layer only, or both layers.

The details of the calculation of the effect of a difference in the elastic modulus are not presented here. It is assumed that the nominal elastic modulus is 2×10^6 psi, the precompression hoop stress is 20,000 psi, and the elastic moduli of the upper and lower halves differ by ±5% from the nominal value.

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Table 2

Azimuthal Error Relationships

Code		Multipliers of ϵ								Number of Occurrences
		$\Delta\theta_1$ Quadrant				$\Delta\theta_2$ Quadrant				
		1	2	3	4	1	2	3	4	
A11	Upper pole piece off center by angle ϵ, ccw	$+\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	$-\frac{1}{2}$	+1	−1	0	0	2
A21	Upper pole piece too wide by angle ϵ on each side	$-\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	$+\frac{1}{2}$	−1	−1	0	0	2
A35	Joints between upper and lower coil above horizontal centerline by angular amount ϵ	+1	+1	−1	−1	0	0	0	0	2

Table 3

Radial Error Relationships

Code	Description	Multipliers of ϵ inner layer		outer layer		Quandrants affected for one occurrence	Number of occurrences
		Δr_1	Δr_2	Δr_1	Δr_2		
R111	Upper half of inner coil too thick by amount ϵ	−1	0	0	0	1, 2	2
R112	Upper half of outer coil too thick by amount ϵ	−1	−1	−1	0	1, 2	2
R31	Radial distance between coils too small by amount ϵ	+1	+1	0	0	1, 2, 3, 4	1
R41	Outer radius of outer coil dis-placed outward by amount ϵ	+1	+1	+1	+1	1	4
R42	Same as R41	+1	+1	+1	+1	1, 2, 3, 4	1

Table 4

Azimuthal Manufacturing Errors

Serial No.		Case	Multiplier, radians	No. of Occurrences
	Pole Piece Centering			
1	Fit of key in keyway			
	Both layers: .001" at r = 42.0 mm	A113	6.05×10^{-4}	2
	Thickness of pole-piece-to-coil insul.			
2	Inner layer: .0005" at r = 24.7 mm	A111	5.14×10^{-4}	2
3	Outer layer: .0005" at r = 34.3 mm	A112	3.70×10^{-4}	2
	Die and punching tolerances			
4	Inner layer: .0005" at r = 24.7 mm	A111	5.14×10^{-4}	2
5	Outer layer: .0005" at r = 34.3 mm	A112	3.70×10^{-4}	2
	Pole Piece Width			
	Thickness of pole-piece-to-coil insul.			
6	Inner layer: .0005" at r = 24.7 mm	A211	5.14×10^{-4}	2
7	Outer layer: .0005" at r = 34.3 mm	A212	3.70×10^{-4}	2
	Die and punching tolerances			
8	Inner layer: .0005" at r = 24.7 mm	A211	5.14×10^{-4}	2
9	Outer layer: .0005" at r = 34.3 mm	A212	3.70×10^{-4}	2
	Midplane Registration			
	Elastic modulus (difference, top to bottom)			
10	Inner layer: ±5%	A351	6.7×10^{-4}	1
11	Outer layer: ±5%	A352	3.7×10^{-4}	1
	Azimuthal width of coil (difference, top to bottom)			
12	Inner layer: .002" at r = 24.7 mm	A351	20.6×10^{-4}	1
13	Outer layer: .002" at r = 34.3 mm	A352	14.8×10^{-4}	1

Table 5

Radial Manufacturing Errors

Serial No.		Code	Multiplier, inches/meters	No. of Occurrences
	Pole piece centering			
	Layer thickness			
14	Inner layer:	R111	$.002/5.08\times10^{-5}$	2
15	Outer layer:	R112	$.002/5.08\times10^{-5}$	2
16	Interlayer insul. thickness	R31	$.0005/1.27\times10^{-5}$	1
	Coil-to-iron insul. thickness			
17	Different for each quadrant	R41	$.0005/1.27\times10^{-5}$	4
18	Same for all quadrants	R42	$.0005/1.27\times10^{-5}$	1
19	Diameter of hole in iron	R42	$.0005/1.27\times10\text{-}5$	1

Effects of Individual Manufacturing Errors on Multipole Coefficients

These are presented in Tables 6 and 7, respectively, for azimuthal and radial errors.

Combined Effects of Manufacturing Errors on Multipole Coefficients

These are presented in Table 8.

Effect of Coil Inside Diameter on Field Quality

Table 8 shows results for LBL-type magnets of 30 and 50 mm i.d., in addition to the proposed 40-mm-i.d. design. For these magnets, all radii have been decreased or increased by 5 mm, while coil thicknesses, coil-to-iron spacing, and block edge angles have been maintained. The manufacturing errors used are the same as those of the 40-mm-i.d. design; they have not been scaled in proportion to the coil diameter.

There are no surprises; the results are about what one would get by simply scaling with coil average radius.

Table 6

Effects of Individual Manufacturing Errors on Field Quality:
Azimuthal Errors

Serial No.	Case			Real or Imaginary	$\frac{\Delta C_1}{C_1}$ x10^4	$\frac{\Delta C_2}{C_1}$ x10^4	$\frac{\Delta C_3}{C_1}$ x10^4	$\frac{\Delta C_4}{C_1}$ x10^4	$\frac{\Delta C_5}{C_1}$ x10^4	$\frac{\Delta C_6}{C_1}$ x10^4
					Normalized multipole coefficients					
1	$A11_3$		Fit of key in keyway	R	6.05	0	< .01	0	.01	0
				I	0	1.50	0	.04	0	.01
		Pole-Piece Centering	Thickness of pole-piece-to-coil insulation:							
2	$A11_1$	Pole-Piece Centering	Inner layer	R	2.33	0	.25	0	.02	0
				I	0	.98	0	.11	0	< .01
3	$A11_2$	Pole-Piece Centering	Outer layer	R	2.02	0	.17	0	< .01	0
				I	0	.21	0	.06	0	<.01
		Pole-Piece Centering	Punching tolerance:							
4	$A11_1$	Pole-Piece Centering	Inner layer	R	Same as above					
				I						
5	$A11_2$	Pole-Piece Centering	Outer layer	R						
				I						
		Pole-Piece Width	Thickness of pole-piece-to-coil insulation:							
6	$A21_1$	Pole-Piece Width	Inner layer	R	0	.37	0	.10	0	.02
				I	2.59	0	.09	0	.05	0
7	$A21_2$	Pole-Piece Width	Outer layer	R	0	.79	0	.01	0	< .01
				I	.75	0	.17	0	.01	0
		Pole-Piece Width	Punching tolerance:							
8	$A21_1$	Pole-Piece Width	Inner layer	R	Same as above					
				I						
9	$A21_2$	Pole-Piece Width	Outer layer	R						
				I						
		Mid-Plane Registration	Elastic modulus tolerance:							
10	$A35_1$	Mid-Plane Registration	Inner layer	R	0	1.37	0	.02	0	< .01
				I	0	0	0	0	0	0
11	$A35_2$	Mid-Plane Registration	Outer layer	R	0	.26	0	.02	0	< .01
				I	0	0	0	0	0	0
		Mid-Plane Registration	Azimuthal coil width:							
12	$A35_1$	Mid-Plane Registration	Inner layer	R	0	4.20	0	.07	0	.03
				I	0	0	0	0	0	0
13	$A35_2$	Mid-Plane Registration	Outer layer	R	0	1.05	0	.09	0	< .01
				I	0	0	0	0	0	0

Table 7

Effects of Individual Manufacturing Errors on Filed Quality:
Radial Errors

Serial No.	Case		Real or Imaginary	$\frac{\Delta C_1}{C_1}$ x10^4	$\frac{\Delta C_2}{C_1}$ x10^4	$\frac{\Delta C_3}{C_1}$ x10^4	$\frac{\Delta C_4}{C_1}$ x10^4	$\frac{\Delta C_5}{C_1}$ x10^4	$\frac{\Delta C_6}{C_1}$ x10^4
				Normalized multipole coeffiecients					
		Layer thickness tol.							
14	$R11_1$	Inner layer	R	0	2.99	0	.14	0	.09
			I	2.60	0	.59	0	.01	0
15	$R11_2$	Outer layer	R	0	5.42	0	.38	0	.14
			I	5.12	0	.73	0	.08	0
16	R31	Interlayer insulation thickness	R	0	0	0	0	0	0
			I	1.1	0	.23	0	.02	0
		Coil-to-iron insulation thickness							
17	R41	Different in each quadrant	R	.97	1.42	.64	.12	.03	.04
			I	1.38	.51	.16	.10	.02	.02
18	R42	Same in all quadrants	R	0	0	0	0	0	0
			I	1.4	0	.16	0	.02	0
19	R42	Radius of hole in iron	R			Same as Serial No. 18			
			I						

Table 8

Combined Effects of Manufacturing Errors on Field Quality

RMS values of multipole coefficients, normalized to nominal dipole field

multipole order n(1)	Real, a_n (skew)			Imaginary, b_n (non-skew)		
	Coil inside diameter, mm					
	30	40	50	30	40	50
2	13. E-4	7.906E-4	5.2E-4	3.2E-4	2.134E-4	1.6E-4
3	16. E-5	7.655E-5	4.3E-5	2.3E-4	1.042E-4	.6E-4
4	12. E-5	4.621E-5	2.2E-5	5.6E-5	2.117E-5	1.0E-5
5	15. E-6	4.474E-6	1.8E-6	4.9E-5	1.306E-5	.5E-5
6	8.1E-5	1.719E-5	.5E-5	14. E-6	2.938E-6	.9E-5
7	15. E-6	2.390E-6	.6E-6	9. E-6	1.522E-6	.4E-6
8	29. E-6	3.427E-6	.7E-6	42. E-7	5.211E-7	1.0E-7
9	18. E-7	1.813E-7	.3E-7	73. E-7	6.564E-7	1.0E-7
10	31. E-7	2.165E-7	.3E-7	1.294E-7	1.294E-7	.2E-7

Normalizing radius = 10 mm

(1)1 = dipole, 2 = quadrupole, etc.

Application of the Method to CBA and Doubler/Saver Magnets

The method presented here has been applied to the CBA and Doubler/Saver dipoles. The numerical values for the manufacturing errors are the same as those used for the LBL magnets; they are not scaled to the magnet size.

A certain amount of fudging had to be done in the interest of saving time. For example, the CBA magnets have two blocks per layer; the representation used here was one block per layer with the Doubler/Saver block angles.

The calculated results, together with experimental results from Erich Willen's paper(2), are presented in Tables 9A and 9B.

Except for the quadrupole terms for the Doubler/Saver magnetrs, the agreement is remarkably good, considering that the inputted data for the manufacturing errors were simply educated guesses. The quad terms are turned out by shimming so the disagreement is understandable.

Comparison of Two Methods for Field-Aberration Calculation

For the 40-mm-i.d. LBL magnet, we also calculate the field aberrations by the following simpler method: Each of the four edges of each of the eight blocks is assigned an error (the same value for all edges). There is no simple relation between such errors and the manufacturing errors, and the conditions of compatibility of the errors is violated. Nevertheless it is a useful method, and a comparison with the method of this report is of interest. The comparison of the results of the two methods is presented in Table 10. The results were fudged to make the rms sums of both the a_n and b_n terms the same for the two methods, which corresponds to an error in all block edge positions of 0.0018 inches.

About all that can be said of the results for certain is that they are different, by as much as a factor of 5 for some components.

Conclusions

The identification of manufacturing errors, and the assignment of numerical values to those errors, are the result of "educated guesses" by the author, and of course the accuracy of the final results in directly affected by those errors. Obviously, those numbers should be refined.

The method used here identifies particular field aberration effects with particular manufacturing errors, and can therefore serve as a basis for specifying tolerances, or altering the design or manufacturing methods. Simply making everything "as good as possible" or "to one mil" might be prohibitively expensive.

Table 9A

Comparison of Calculated and Measured Field Aberrations: CBA Dipoles

	a_n			b_n		
n	Calc.		Meas.	Calc.		Meas.
2	9.1E-5	>	5.0E-5	3.6E-5	>	2.0E-5
3	3.8E-6	≅	3.1E-6	2.9E-6	<	8.8E-6
4	9.9E-7	≅	9.4E-7	3.6E-7	≅	3.5E-7
5	2.2E-8	<	8.0E-8	5.7E-8	>	2.7E-7
6	2.2E-8	≅	2.4E-8	5.1E-9	<	1.8E-8
7	1.6E-9	<	4.1E-9	1.5E-9	<	4.1E-9
8	8.2E-10		--	1.4E-10		--
9	3.2E-11		--	6.9E-11		--
10	2.6E-13		--	5.2E-12		--

Table 9B

Comparison of Calculated and Measured Field Aberrations: Doubler/Saver Dipoles

	a_n			b_n		
n	Calc.		Meas.	Calc.		Meas.
2	3.8E-4	>>	2.0E-5	7.2E-4	>>	1.9E-5
3	2.4E-5	>	1.8E-5	1.1E-4	<	4.8E-5
4	1.1E-5	≅	8.9E-6	1.9E-5	>	4.7E-6
5	4.1E-7	<	1.1E-6	2.7E-6	≅	3.2E-6
6	6.4E-7	≅	5.2E-7	7.7E-7	<	3.0E-7
7	7.1E-8	>>	1.1E-8	1.1E-7	<	2.0E-7
8	6.6E-8	>	3.8E-8	7.6E-8	>	2.5E-8
9	4.2E-9	<	2.4E-8	1.2E-8	>	1.9E-9
10	5.4E-9	<	8.6E-9	9.2E-9	>	5.3E-9

Table 10

Comparison of Two Methods for Calculating Effect of Dimensional Errors on Field Aberrations

	a_n (real) method*		b_n (imag.) method*	
n	1	2	1	2
2	7.9E-4	6.0E-4	2.1E-4	4.7E-4
3	7.7E-5	24. E-5	1.0E-4	1.9E-4
4	4.1E-5	5.1E-5	2.1E-5	8.4E-5
5	4.5E-6	10.9E-6	1.3E-5	2.6E-5
6	1.7E-5	1.1E-5	2.9E-6	10.7E-6
7	2.4E-6	6.8E-6	1.5E-6	5.5E-6
8	3.4E-6	2.8E-6	5.2E-7	25. E-7
9	1.8E-7	3.8E-7	6.6E-7	11.4E-7
10	2.2E-7	2.6E-7	1.3E-7	4.3E-7

*Method 1 is the method described in the Introduction. Method 2 applies a .00181-inch error to all block boundary positions.

References

1. Math Backup for LBL-17050, R. Meuser, LBL Engineering Note 6208, Jan. 1984.

2. Magnetic Imperfections, Eric Willen. In these proceedings.

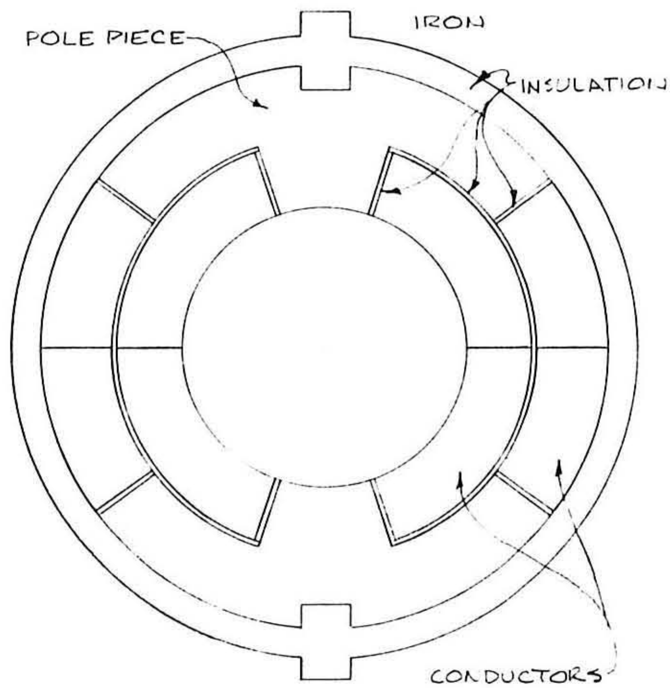

Fig. 1 Schematic cross section of LBL dipole magnet for the CBA.

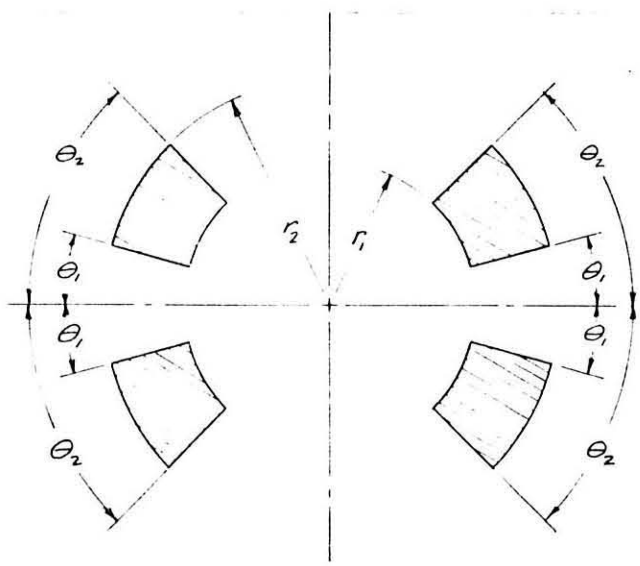

Fig. 2 Nomenclature for coil current block outline dimensions.